Charge symmetry breaking in ${}^{4}_{\Lambda}$He - ${}^{4}_{\Lambda}$H hypernuclei

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Introduction

The experimentally observed large charge symmetry breaking (CSB) in the ${}^{4}_{\Lambda}$He - ${}^{4}_{\Lambda}$H isomutiplets is a long standing problem in strangeness nuclear physics. In 2015, with the advent of modern HPGe detectors at J-PARC [1], the binding energy(B.E.) of ${}^{4}_{\Lambda}$He hypernucleus for both ground (0^+) and excited (1^+) states were updated to 2.39±0.05 MeV and 0.984±0.05 MeV, respectively. Recently at the Mainz Microtron MAMI, the high-resolution spectroscopic studies [2, 3] were performed to extract the ground state B.E. of ${}^{4}_{\Lambda}$H hypernucleus. Analyzing the pion-decay in strangeness electro-production, the ground state B.E. value of ${}^{4}_{\Lambda}$H hypernucleus is updated to 2.157±0.077 MeV. This updated value of the ground state B.E. of ${}^{4}_{\Lambda}$H is used together with the ground state B.E. of ${}^{4}_{\Lambda}$He hypernucleus obtained from nuclear emulsion experiments to explain the ground state CSB in ${}^{4}_{\Lambda}$He - ${}^{4}_{\Lambda}$H hypernuclei. Moreover, recently updated B.E. values of 1^+ state for both hypernuclei from γ-ray spectroscopy provides the B.E. difference in excited states. The B.E. difference in the A=4 mirror pair is reduced from its long accepted value (0.35±0.06 MeV) to ∼ 0.23±00.5 MeV for 0^+ state and (0.21±0.06 MeV) to ∼ -0.08 MeV for 1^+ state, respectively. However, for the first time, energy difference for excited state are found negative. In this study, we performed a fully correlated Variational Monte Carlo (VMC) study of ${}^{4}_{\Lambda}$He - ${}^{4}_{\Lambda}$H hypernuclei taking into consideration of CSB potential to investigate 0^+ - 1^+ splitting and CSB effects.

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Formalism

The Hamiltonian H of a hypernucleus with a Λ hyepron and $A-1$ nucleons can be written as

$$H = H_{\rm NC} + H_{\Lambda} \tag{1}$$

where $H_{\rm NC}$ and H_{Λ} are Hamiltonian of the core nucleus and Λ baryon, respectively and given by

$$H_{\rm NC} = T_{\rm NC} + \sum_{i<j} v_{ij} + \sum_{i<j<k} V_{ijk}, \tag{2}$$

$$H_{\Lambda} = T_{\Lambda} + \sum_{i} v_{\Lambda i} + \sum_{i<j} V_{\Lambda ij} \tag{3}$$

where v_{ij}, V_{ijk}, $v_{\Lambda i}$, and $V_{\Lambda ij}$ are the two-and three-body potentials for NN and ΛN sector, respectively. The two-body ΛN potential can be written as

$$v_{\Lambda N} = v_0(r_{\Lambda N}) + v^x(r_{\Lambda N}). \tag{4}$$

where the direct potential includes a Woods-Saxon repulsive term and a two-pion exchange attractive term

$$v_0(r_{\Lambda N}) = \frac{W_0}{1 + exp\{(r-R)/a\}} - v_{2\pi} \tag{5}$$

To calculate CSB contribution in ${}^{4}_{\Lambda}$He - ${}^{4}_{\Lambda}$H hypernuclei, one can include a CSB potential $\tau v^{CSB} T^2_{\pi}(r_{\Lambda i})$ with two-pion exchange attractive potential as

$$v_{2\pi} = \bar{v} T^2_{\pi}(r_{\Lambda i}) + \tau v^{CSB} T^2_{\pi}(r_{\Lambda i}). \tag{6}$$

The Variational Wavefunction (WF) of a hypernucleus which induces all important correlations that are significant to energy can be written as

$$|\Psi\rangle = \left[1 + U^3 + \sum_{i<j}^{A-1} U_{ij}^{LS}\right]\left[\prod_{j=1}^{A-1}(1 + u_{\Lambda j}^{\sigma})\right] \left[\prod_{i<j}^{A-1}(1 + U_{ij})\right]\Psi_J + \eta\sum_{n=1}^{A-1}[1 + U^3] \left[S\prod_{i<j}^{A-1}(1 + U_{ij})\right]u_{\Lambda n}^{x}P_x\Psi_J, \tag{7}$$

where i, j, k, represent nucleons and η is variational parameter. The Jastrow WF Ψ_J which include two- and three-baryon central correlations is given by

$$\Psi_J = \left[\prod_{j<k}^{A-1} f_{\Lambda jk}^{c}\right]\left[\prod_{j=1}^{A-1} f_{\Lambda j}^{c}\right] \left[\prod_{i<j<k}^{A-1} f_{ijk}^{c}\right]\left[\prod_{i<j}^{A-1} f_{ij}^{c}\right]\Psi_{JT} \tag{8}$$

More detail about two- and three-body potentials and the WF can be found in Ref. [6].

Results and discussion

Many theoretical attempts were made in the past to reproduce the experimentally observed B.E. and also to explain the observed CSB in A=4 mirror isomultiplets but except few [4, 5], others could not successful in reproducing the experimental values. Recently, a VMC study was carried out by taking the average B.E. of the ${}^{4}_{\Lambda}$He - ${}^{4}_{\Lambda}$H hypernuclei as 2.22(4) MeV but without considering CSB potential [6, 7]. We performed a VMC study including CSB potential along with all dynamical correlations that affects the B.E. of ${}^{4}_{\Lambda}$He and ${}^{4}_{\Lambda}$H hypernuclei. For strange sector, we use phenomenological charge symmetric ΛN and ΛNN potentials, while the Argonne NN(AV18) and Urbana NNN(UIX) potentials are used for the non-strange sector. To assess the CSB effect, we include a CSB potential $\tau v^{CSB} T_{\pi}^{2}(r_{\Lambda i})$. We choose the same parameters set that used in Ref. [6]. We notice that the variational parameters that reproduce the average value of

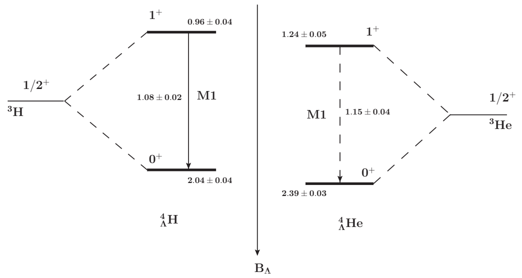

FIG. 1: Figure shows the experimentally observed 0^+ and 1^+ splitting in ${}^{4}_{\Lambda}$He - ${}^{4}_{\Lambda}$H hypernuclei based on old emulsion data.

B.E. = 2.22(4) MeV for ${}^{4}_{\Lambda}$He - ${}^{4}_{\Lambda}$H hypernuclei are producing the ground state B.E. of ${}^{4}_{\Lambda}$He as 2.67(3) MeV and ground state B.E. of ${}^{4}_{\Lambda}$H as 2.28(4) MeV. The values of B.E. for excited states of ${}^{4}_{\Lambda}$He and ${}^{4}_{\Lambda}$H hypernuclei are found to be 1.13(3) MeV and 1.02(2) MeV, respectively. The values of the B.E. for both 0^+ and 1^+ states are found slightly larger than experimentally observed values. This will results in large 0^+ - 1^+ splitting in comparison to the experimentally observed 0^+ - 1^+ splitting. After correcting the Coulomb rearrangement energy which is ∼0.05 MeV in ${}^{4}_{\Lambda}$He hypernucleus the CSB contribution is found to be ≈0.43 MeV which is quite larger as compared to recently updated value of CSB in A=4 isomultiplets. Thus, our VMC calculation sugests a large CSB effect in A=4 isomultiplets.

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